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Longitudinal Mode Beat Intensities in a CW HF Chemical Laser

Prepared by C. P. WANG and R. L. VARWIG
Aerophysics Laboratory

19 February 1976

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LONGITUDINAL MODE BEAT INTENSITIES IN A CW HF CHEMICAL LASER

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ABSTRACT

Longitudinal mode beat intensities in a free-running cw HF chemical laser have been investigated. A simple expression has been derived that describes the variation of beat intensity with tuning frequency. Experimental observations of the variation of beat intensity with tuning frequency in a HF chemical laser agree with the theoretical prediction.

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I. INTRODUCTION

When two or more longitudinal modes oscillate in a laser, mode pulling, mode pushing, mode competition, locking, population pulsations, and related phenomena occur. These have been described by Lamb's semiclassic theory[1] and by various numerical computations.[2-5] Experimental observations of one or more of these phenomena have also been made on He-Ne[3,6] and other lasers.[7-9]

The cw HF chemical laser is a potential high-efficiency, high-power gas laser.[10,11] Its gain medium, however, is rather complex due to the nature of the chemical reaction, rotation-vibration transitions, medium nonuniformity, and mixed inhomogeneous-homogeneous behavior. Hence, it is important to examine the mode competition and mode-pulling behavior in a HF chemical laser. Furthermore, on the basis of the beat frequency between longitudinal modes and the mode-pulling effect in a high-gain medium, a new active frequency stabilization scheme was conceived.[8] Because of the strong mode competition, the key to the success of this new scheme is whether or not a steady beat signal can be obtained.

The results of a study of the longitudinal mode competition in a cw HF chemical laser are reported here. On the basis of Lamb's semiclassic theory, a simple expression is formulated to describe the effect of mode competition and to calculate the variation of beat intensity with tuning frequency. Experimental observations are also given of the Lamb dip, mode competition, mode pulling, beat frequency, and beat intensity in a cw HF chemical laser.

II. THEORY

The basic equations of Lamb's semiclassic description of a multimode laser are[1]

$$\frac{dI_n}{dt} = 2I_n(a_n - \beta_n I_n - \sum_{m \neq n} \theta_{nm} I_m) \quad , \tag{1}$$

where I_n is the dimensionless intensity for mode n, a_n is the net gain coefficient for mode n, θ_{nm} is the cross-saturation coefficient by mode m, β_n is the self-saturation coefficient for mode n, and t is time. These coefficients a_n, β_n, and θ_{nm} are functions of population inversion, cavity loss, and upper- and lower-state decay rates and include spontaneous and collisional decay, Doppler width Ku, distribution of active medium in the resonator, difference frequency $\nu_m - \nu_n$, and location of the oscillation frequencies ν_n with respect to line center ω. Exact expressions for these coefficients have been given by Lamb[1] and by Sayers and Allen.[2]

For stationary states, $dI_n/dt = 0$. Then, Eq. (1) becomes

$$a_n - \beta_n I_n - \sum_{m \neq n} \theta_{nm} I_m = 0 \quad , \tag{2}$$

where a_n corresponds to the net single-pass unsaturated gain of mode n, $\beta_n I_n$ is the decrease in that net gain due to saturation of the gain by mode n, and $\theta_{nm} I_m$ is the decrease in the gain due to the saturation by mode m.

The frequency-determining equations, namely, the frequency shift of mode n caused by anamolous dispersion, have been derived by Lamb[1] and are not discussed here. This is because, for free-running lasers, phase relations between modes are random and, hence, can be ignored.

For single-mode oscillation, Eq. (2) is simply

$$I_n = \frac{a_n}{\beta_n} \quad . \tag{3}$$

In an inhomogeneously broadened gain medium, I_n can be expressed as[1]

$$I_n = 8 \frac{\exp\left[-(\omega - \nu_n)^2/(Ku)^2\right] - N^{-1}}{\gamma_{ab}\left[1 + \frac{\gamma^2}{\gamma^2 + (\omega - \nu_n)^2}\right]} \quad , \tag{4}$$

where N is the relative excitation, which is the ratio of average population inversion and population inversion at threshold, γ_{ab} is the spontaneous emission and inelastic collision contribution to decay of atomic dipole, and γ is the atomic dipole decay constant.

From Eq. (4), the cut-off frequency ω_c can be obtained by letting $I_n = 0$:

$$\omega_c = \omega \pm Ku\sqrt{\ln N} \quad , \tag{5}$$

and the dip condition can be obtained by letting $d^2 I_n/d\nu_n^2 \geq 0$:

$$N \geq 1 + 2\left(\frac{\gamma}{Ku}\right)^2 \quad . \tag{6}$$

For two-mode operation, the solution of Eq. (2) is

$$I_1 = \frac{a_1\beta_2 - a_2\theta_{21}}{\beta_1\beta_2 - \theta_{12}\theta_{21}} \quad ,$$

$$I_2 = \frac{a_2\beta_1 - a_1\theta_{12}}{\beta_1\beta_2 - \theta_{12}\theta_{21}} \quad . \tag{7}$$

Because all these coefficients are complicated functions of ν_n and physical parameters of the gain medium, only numerical solutions were obtained earlier. These numerical solutions show rapid change in mode intensities with change in frequency because of strong mode competition. In order to gain some insight into Lamb's equations and to illustrate the physics of the mode competition effect, a simple model is formulated. Let

$$\beta = \sqrt{\beta_1\beta_2} \quad , \qquad \theta = \sqrt{\theta_{21}\theta_{12}} \quad ,$$

$$s = \frac{1}{2}\left[a_1\sqrt{\frac{\beta\theta}{\beta_1\theta_{21}}} + a_2\sqrt{\frac{\beta_1\theta_{21}}{\beta\theta}}\right] \quad ,$$

$$d = \frac{1}{2s}\left[a_1\sqrt{\frac{\beta\theta}{\beta_1\theta_{21}}} - a_2\sqrt{\frac{\beta_1\theta_{21}}{\beta\theta}}\right] \quad ,$$

$$\beta' = \beta/\theta \quad .$$

Then,

$$I_1 I_2 = \frac{s^2}{\theta^2}\left[\frac{1}{(\beta' + 1)^2} - \frac{d^2}{(\beta' - 1)^2}\right] \tag{8}$$

Now let the mode spacing be $\nu_2 - \nu_1 = \Delta$ and the center frequency be $1/2 (\nu_1 + \nu_2) = \omega + \Omega$, where $\Omega = 0$ for mid-tuning, and Ω varies between 0 and $\Delta/2$. Then, all the variable β, θ, s, and d are functions of Ω (see Appendix).

Because both s and θ are nonzero, the condition for positive beat intensity $I_1 I_2 \geq 0$, is simply $\beta' \leq \beta_-$ or $\beta' \geq \beta_+$, where $\beta_- = (1 - d)/(1 + d)$, and $\beta_+ = (1 + d)/(1 - d)$. In region $\beta_- < \beta' < \beta_+$, Eq. (8) is negative, and we set $I_1 I_2 = 0$ because mode intensities I_1 and I_2 are positive quantities. If either I_1 or $I_2 = 0$, Eq. (7) is no longer valid, and the single-mode solution Eq. (3) has to be used.

For the cw HF chemical laser studied here, both the ratio of the collision-broadened linewidth to the Doppler linewidth and the ratio of cavity intensity to saturation intensity are much smaller than one. Hence, in the range of interest, $0 \leq \Omega \leq \Delta/2$, all the variables s, d, θ, and β' are nonzero and are monotonic functions of Ω, except for d = 0 at $\Omega = 0$. In general, these variables can be approximated by a second-order polynomial of Ω. The asymptotic form of these variables and a numerical example are given in the Appendix. Both s and θ vary less than 50% in the range $0 \leq \Omega \leq \Delta/2$.

Because s and θ are nonzero, monotonic, and slowly varying functions of Ω, the locations of the maximum values of $I_1 I_2$ and $I_1 I_2\, \theta^2/s^2$ are very close. Hence, in order to find the value of Ω at which $I_1 I_2$ is a maximum, we can let $d(I_1 I_2 \theta^2/s^2)/d\beta' = 0$ and solve for β'. Since $d < 1$, we have only one real root: $\beta_m = (1 + d^{2/3})/(1 - d^{2/3})$. The maximum beat intensity at β_m is

$$\left(I_1 I_2 \frac{\theta^2}{s^2}\right)_{\beta' = \beta_m} = \frac{1}{4}(1 - d^{2/3})^3 \qquad (9)$$

In an analysis of two-mode operation, Lamb[1] introduced a coupling parameter $c \equiv \theta_{12}\theta_{21}/\beta_1\beta_2$ and observed that the coupling is weak or strong as $c < 1$, $c > 1$, respectively. Also, two-mode operation is unstable when $c > 1$. In terms of the present notation, $c = (1/\beta')^2$. We also note, from the definition of β_- and β_+, that $\beta_- < 1$ and $\beta_+ > 1$.

The variation of beat intensity with β' is plotted in Fig. 1. In region $\beta' < \beta_-$ i.e., $c > 1$, the coupling is strong, and the lasing is unstable. In region $\beta' > \beta_+$ i.e., $c < 1$, the coupling is weak, and the lasing tends to be stable.

The variation of $I_1 I_2$ with Ω can be obtained by substituting the relation $\beta' = \beta'(\Omega)$ into Eq. (8). Since β' can be approximated as a second-order polynomial of Ω, the variation of beat intensity with Ω is similar in Fig. 1a, except that the horizontal scale is shifted, stretched, or compressed nonuniformly. A typical plot is shown in Fig. 1b.

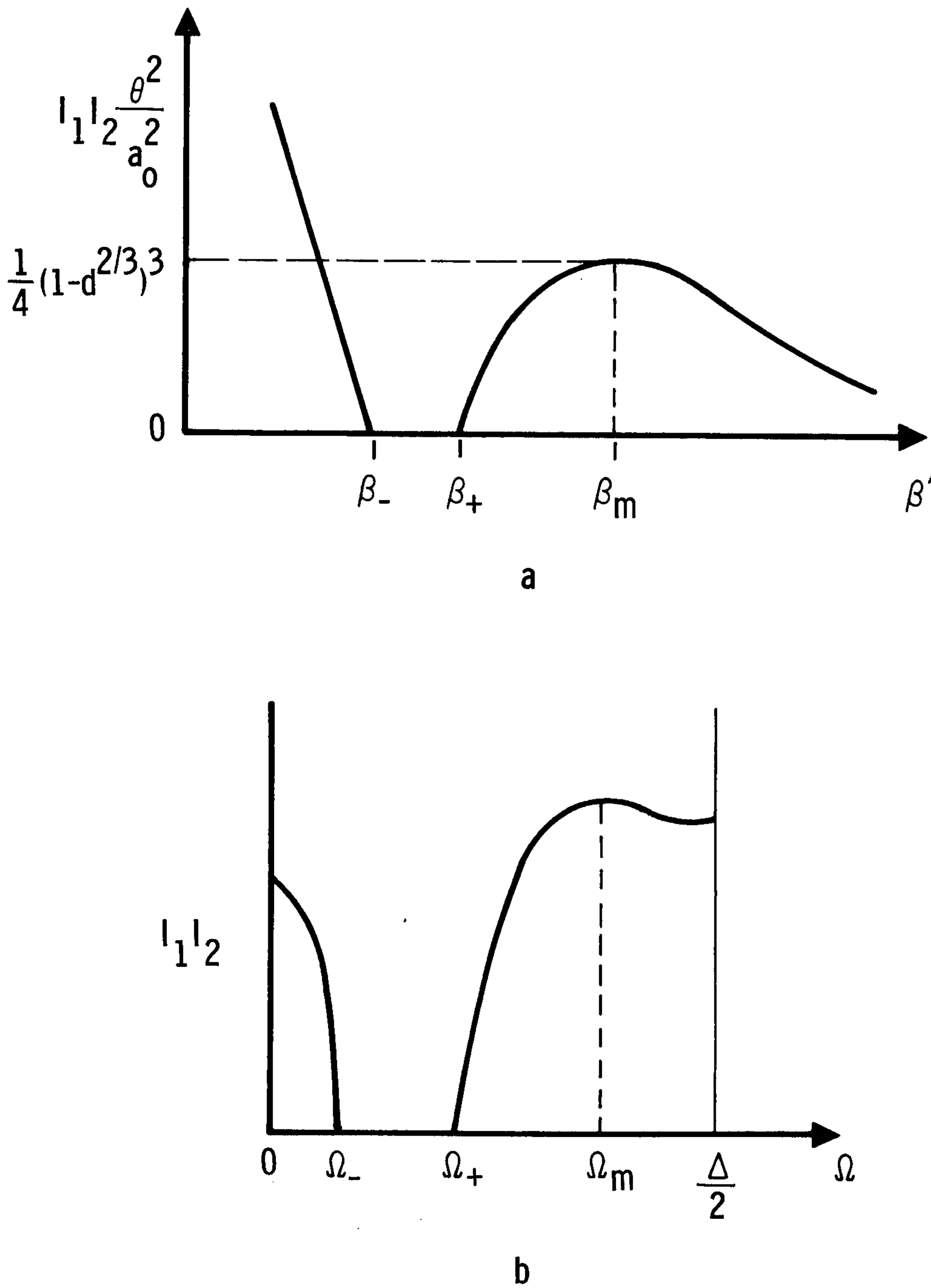

Figure 1. Characteristic Shape of the Beat Intensity Distribution vs β' and Ω

III. EXPERIMENTAL RESULTS

In order to verify the theory, experiments were carried out with a cw HF chemical laser. The laser output spectra, beat frequencies, and beat intensities were measured by using a confocal scanning Fabry-Perot interferometer, spectrum analyzer, and fast InAs detector. The cw HF chemical laser used was described in an earlier paper.[9] Briefly, F atoms are generated by a discharge in a gas mixture of He, O_2, and SF_6. The latter is mixed with H_2, which is injected just upstream of a transverse optical cavity. The cavity pressure could vary from 5 to 15 Torr. Typical single-line output at 2.87 μm is 0.5 W. The gain medium is 10 cm long, and there is a small signal gain of about 0.05 cm^{-1}.

A stable resonator was used that had a 2-m radius-of-curvature total reflector (reflectivity > 95%) and a flat grating (reflectivity 80%) as the output coupling. These were separated by distances of L = 30.6 cm and L = 162.6 cm for single-mode and two-mode operation, respectively. A TEM_{00}-mode output beam was obtained by using a variable aperture inside the resonator. The total reflecting mirror was mounted on a PZT driver, which could move the mirror and scan the laser frequency across the gain linewidth. A schematic of the experimental arrangement is shown in Fig. 2.

In order to measure the beat frequency of the longitudinal modes, a room-temperature InAs detector with risetime less than 3 nsec was used. The beat signal was displayed on a Tektronix 7094 oscilloscope and analyzed by a Hewlett-Packard spectrum analyzer, model 8553B. A Burleigh 25-cm confocal scanning Fabry-Perot interferometer with free spectrum range of 300 MHz and resolution better than 5 MHz was used to analyze the laser output frequency spectrum. The laser and all the optics were mounted on a NRC vibration isolated table.

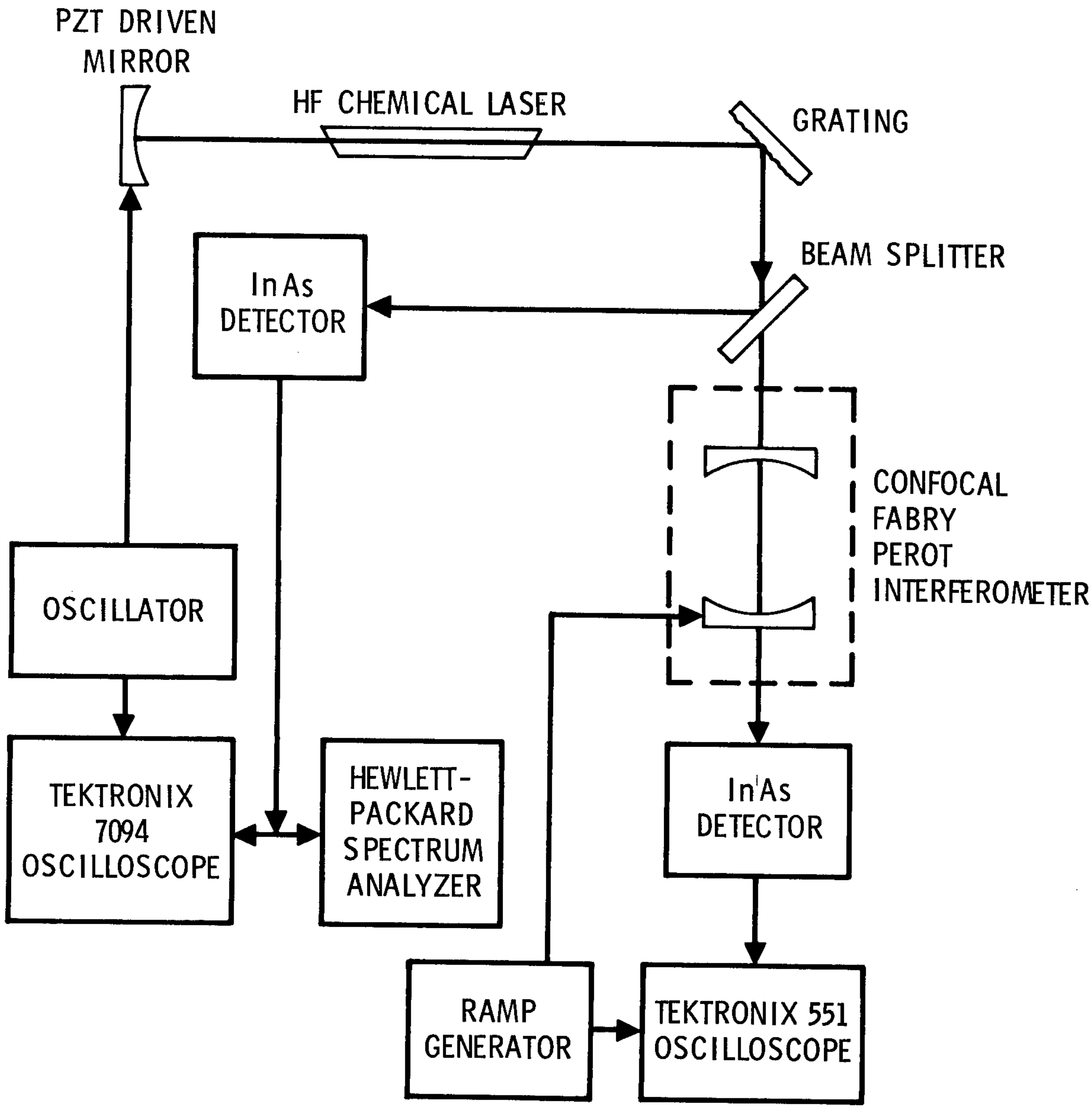

Figure 2. Block Diagram of the Experimental Apparatus

For single-mode operation, a cavity length L = 30.6 cm was chosen. The empty cavity mode spacing is then 490 MHz, which is larger than the gain linewidth. The mode frequency can be continuously scanned through the gain linewidth by applying a high voltage on the PZT driver. A typical single-mode laser output intensity as a function of mode frequency is shown in Fig. 3. The Lamb dip in the center is clearly distinguishable, and the cut-off frequency can be determined. Similar Lamb dip was also observed in a HF chemical laser by Glaze.[12]

The saturation behavior results in the appearance of the Lamb dip [Eqs. (4) and (5)]. Its width is related to the radiative interaction width of individual molecules. Hence, information on collision effects can be obtained by investigating the pressure-dependent behavior of the dip.[12, 13]

For two-mode operation, a cavity length L = 162.6 cm was chosen. The empty cavity mode spacing is then 92.3 MHz, which is much smaller than the gain linewidth. Hence, multimode operation can be achieved.

Typical laser output frequency spectra obtained by the scanning Fabry-Perot interferometer are shown in Fig. 4. The vertical scale is the laser intensity, and the horizontal scale is the frequency, swept at 28 MHz/div. The small bump in front of the peak is caused by a misalignment of the Fabry-Perot interferometer to reduce the coupling between the laser and the Fabry-Perot interferometer. Both traces were obtained by the same setup but were taken at 5 sec separation. The large variations of these two mode intensities indicate the strong mode competition effect.

A typical beat signal intensity distribution as a function of tuning frequency is shown in Fig. 5. The upper trace is the driving voltage of the PZT driver; the lower trace is the beat signal. Because of the low sweep speed, each individual oscillation of the beat signal can not be seen. However, the envelop, which is the beat intensity, is clearly discernable. The shape of the envelop agrees very well with the theoretical prediction (Fig. 1).

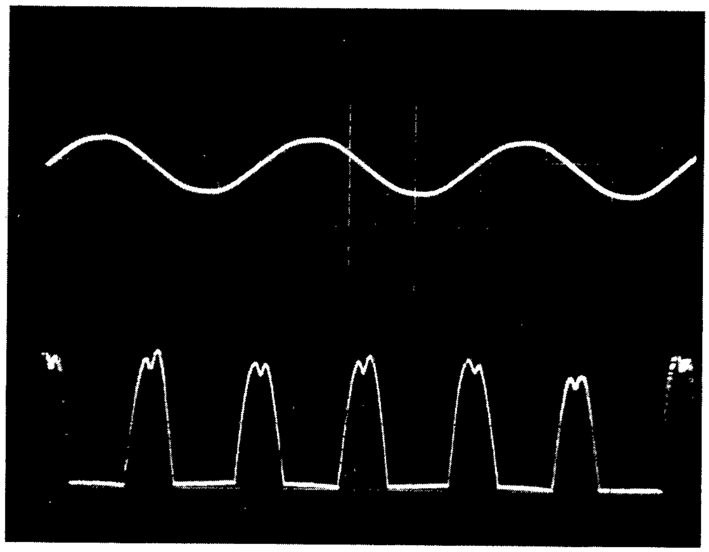

Figure 3. Oscilloscope Trace of a Single-Mode Laser Output Intensity vs Mode Frequency. Upper trace: driving voltage, 500 v/div, which is equivalent to 400 MHz/div. Lower trace: mode intensity, 200 mV div. Sweep speed, 5 msec/div.

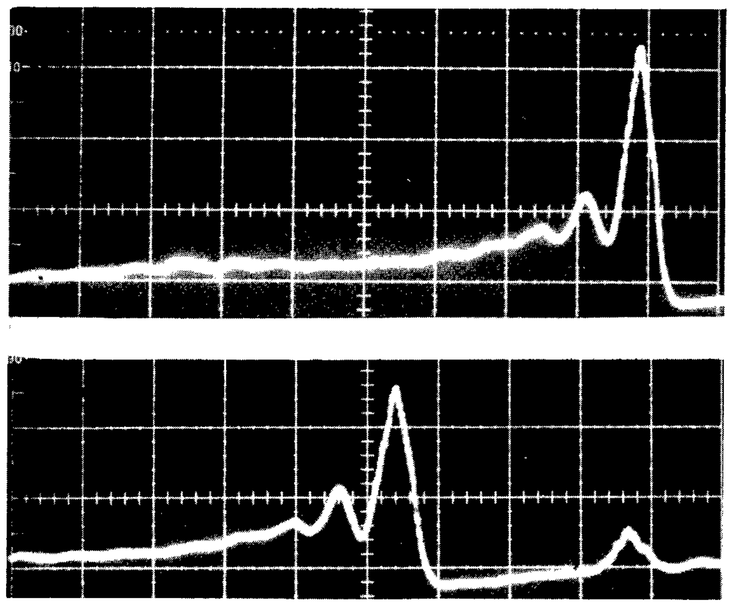

Figure 4. Typical Two-Mode Laser Output Spectra Obtained by a Scanning Fabry-Perot Interferometer. Verticle scale, 50 mV/div; horizontal scale, 28 MHz/div; sweep duration, 50 msec. Lower trace taken 5 sec after upper trace.

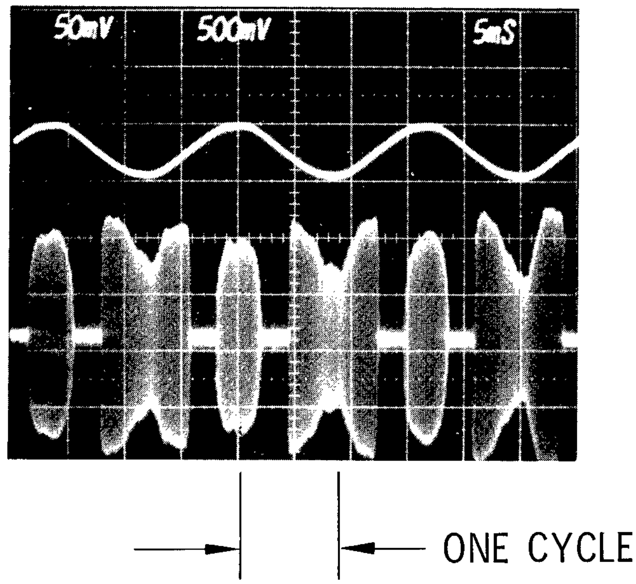

Figure 5. Oscilloscope Trace of Beat Intensity vs Frequency Ω. Upper trace: driving voltage, 500 V/div, which is equivalent to 75 MHz/div. Lower trace: beat signal, 50 mV/div. Sweep speed, 5 msec/div.

For the beat frequency, two consecutive spectra with time separation of 2 sec are shown in Fig. 6. The center frequency was 88 MHZ, which agrees with Fig. 4. The beat frequency is smaller than the empty cavity mode spacing value of 92.3 MHz because of the mode pulling effect.[7, 9, 14] The width of the spectra is the result of a short-time (10 msec sweep duration) laser frequency instability, and the separation of these two spectra is the result of a long-time (2 sec separation) instability. On the basis of the theory developed in Ref. 9, these correspond to a short-time frequency instability of 10 MHz and a long-time (2 sec) frequency instability of 15 MHz. These agree with the results obtained by the scanning Fabry-Perot interferometer.

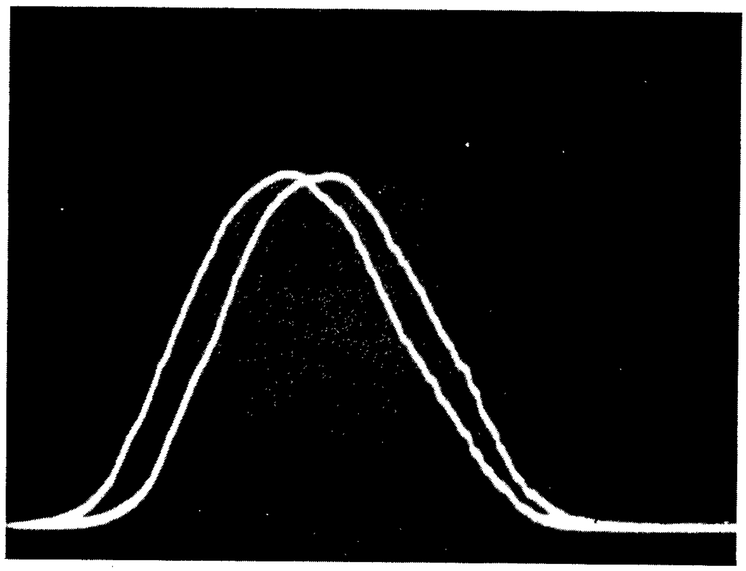

Figure 6. Frequency Spectrum of Beat Signal. Center frequency, 88 MHz; horizontal scale, 100 kHz/div; verticle scale, log intensity. Two consecutive sweeps separated by 2 sec are shown. Time duration for each complete sweep, 10 msec.

IV. CONCLUSIONS

A simple expression was obtained for variation of beat intensity with a parameter β', which is a slowly varying function of the tuning frequency Ω. This expression illustrates the general behavior of the beat intensity versus tuning frequency that results from mode competition effects. Furthermore, the results are useful for identifying regions of stable two-mode operation for use of active frequency stabilization of Ref. 9. Experimental observations are in good agreement with the theory.

APPENDIX: EXACT AND APPROXIMATE EXPRESSIONS FOR THE GAIN AND SATURATION COEFFICIENTS

Exact expressions for the coefficients from Ref. 1:

$$a_n = 4\{\exp[-(\omega - \nu_n)^2/(Ku)^2]\, N - 1\}\, F_3$$

$$\beta_n = [1 + \mathscr{L}(\omega - \nu_n)]\, F_3$$

$$\theta_{mn} = \left[\mathscr{L}\left(\omega - \frac{\nu_n}{2} - \frac{\nu_m}{2}\right) + \mathscr{L}\left(\frac{\nu_m}{2} - \frac{\nu_n}{2}\right)\right] F_3$$
$$+ \frac{1}{2}\,\frac{\gamma_a\gamma_b\gamma}{\gamma_{ab}}\, \mathrm{Rl}\left\{[\mathscr{D}_a(\nu_m - \nu_n) + \mathscr{D}_b(\nu_m - \nu_n)]\right.$$
$$\left.\times\left[\mathscr{D}(\omega - \nu_n)\frac{N_{2(m-n)}}{\overline{N}} + \mathscr{D}\,\frac{\nu_m}{2} - \frac{\nu_n}{2}\right]\right\} F_3$$

where $\mathscr{L}(x) \equiv \gamma^2/(\gamma^2 + x^2)$; $\mathscr{D}_a(x) \equiv (\gamma_a + ia)^{-1}$; Rl is the real part; υ_n is the laser frequency in mode n; γ_a, γ_b are upper and lower-level decay constants; $\gamma_{ab} = 1/2(\gamma_a + \gamma_b)$; γ is the atomic dipole decay constant; ω is the line center frequency; $F_3 = (1/8)(\upsilon/Q_n)N$ is the third-order factor in laser coefficients; N is the relative excitation; N_2 is the spatial Fourier component of the population inversion density; υ/Q_n is the cavity bandwidth; and Q_n is the cavity quality factor for mode n.

The asymptotic form when γ_a, γ_b, $\gamma < \Delta <$ Ku, and $0 \leq \alpha \leq 1/2$ are:

$$\beta \simeq F_3(A + B\alpha^2)^{1/2}$$

$$\theta \simeq F_3(C + D\alpha^2)^{1/2}$$

$$s \simeq F_3\left(E + \frac{\alpha}{N}\right)$$

$$d \simeq F_3 \frac{\alpha}{s} = \alpha\left(E + \frac{\alpha}{N}\right)^{-1}$$

where A, B, C, D, and E are constants of the order of one, and $\alpha = \Omega/\Delta$.

For a particular case when $\gamma_a = \gamma_b = \gamma_{ab} = \gamma = \Delta/2$, $N_2 = -1/2$, and $Ku = 2\Delta$, we have, when $\alpha = 0$, $\beta = 1.32$, $\theta = 1.45$, $\beta' = 0.91$, $A = 1$, $s = 4$, and $d = 0$; and $\alpha = 1/2$, $\beta = 1.28$, $\theta = 1.06$, $\beta' = 1.20$, $A = 0.93$, $s = 4 + 1/2N$, and $d = 1/2\ (4 + 1/2N)^{-1}$. Hence, β, θ, β', and s are slowly varying functions of Ω for $0 \leq \Omega/\Delta \leq 1/2$.

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